The diffuse GeV-TeV γ-ray emission of the Cygnus region

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ABSTRACT

Recently the Milagro experiment observed diffuse multi-TeV gamma ray emission in the Cygnus region, which is significantly stronger than what predicted by the Galactic cosmic ray model. However, the sub-GeV observation by EGRET shows no excess to the prediction based on the same model. This TeV excess implies possible high energy cosmic rays populated in the region with harder spectrum than that observed on the Earth. In the work we studied this theoretical speculation in detail. We find that, a diffuse proton source with power index $\alpha_p \lesssim 2.3$, or a diffuse electron source with power index $\alpha_e \lesssim 2.6$ can reproduce the Milagro's observation without conflicting with the EGRET data. Further detections on neutrinos, a diagnostic of the hadronic model, and hard X-ray synchrontron radiation, a diagnostic of the lepton model, help to break this degeneracy. In combination with the gamma ray observations to several hundred GeV by Fermi, we will be able to understand the diffuse emission mechanisms in the Cygnus region better.

Subject headings: ISM: general — cosmic rays — acceleration of particles — gamma rays: theory

1. Introduction

The Galactic diffuse gamma-ray emission provides important information on the origin and propagation of the Galactic cosmic rays (GCRs) (Strong et al. 2000, 2004b). In general, there exist three possible mechanisms for the diffuse gamma-ray emission: decay of neutral pion produced by hadronic interaction between cosmic ray (CR) nuclei and interstellar gas; inverse Compton (IC) scattering between CR electron and interstellar radiation field (ISRF);

and the bremsstrahlung radiation by interaction between CR electron and interstellar gas. In addition, dark matter annihilation is emerging as an alternative possibility to the diffuse γ-rays (de Boer 2005; de Boer et al. 2005; de Boer 2007; Bi et al. 2008a,b).

The Cygnus region, defined as $65^\circ < l < 85^\circ$ and $-3^\circ < b < 3^\circ$ following the Milagro measurements, is rich in molecular clouds and is one of the richest star formation regions in the Galaxy (Dobashi et al. 1996; Schneider et al. 2006). Observations in radio (Piddington & Minnett 1952), infrared (Knödlseder 2000; Comerón et al. 2002; Hanson 2003), optical (Dickel et al. 1969), X-ray (Giacconi et al. 1967) and γ-ray (Chen et al. 1996) bands found many interesting sources in this region. These sources have provided us valuable information about the astrophysical processes in this region. Ground-based very high energy (VHE) γ-ray observatories also detected TeV γ-ray emissions in the Cygnus region (Aharonian et al. 2002; Abdo et al. 2007a). Such detection is of great importance for CR physics, since it indicates the existence of high energy CR accelerators. Especially the Milagro experiment[1] has made remarkable progress recently.

The Milagro experiment discovered two sources together with a diffuse TeV γ-ray emission in the Cygnus region (Abdo et al. 2007a, 2008, 2007b). For the two sources, MGRO J2031+41 is possibly the counterpart of the unidentified TeV source TeV J2032+4130, first discovered by HEGRA (Aharonian et al. 2002), and MGRO J2019+37 is observed for the first time without an obvious counterpart. There are extensive discussions about the nature of the two TeV sources (Aharonian et al. 2002; Butt et al. 2003; Mukherjee et al. 2003; Beacom & Kistler 2007). However, no consensus has been reached yet. As for the diffuse γ-ray emission, the Milagro measurement shows an evident excess (hereafter "TeV excess") compared with the diffuse emission predicted by the Galactic cosmic ray model GALPROP (~ 7 times of the conventional model prediction and ~ 2 times of the optimized model prediction, Abdo et al. 2008). On the other hand, the sub-GeV band measurements by EGRET are well consistent with the GALPROP prediction (Hunter et al. 1997; Abdo et al. 2007a) [2].

The "TeV excess" may be due to some unidentified TeV sources or diffuse high energy proton or electron population in the Cygnus region(Abdo et al. 2007a). If the latter is true we can draw two general conclusions according to the Milagro and EGRET data: 1), the

[1]Milagro homepage, http://umdgrb.umd.edu/cosmic/milagro.html

[2]It should be pointed out that, there are "GeV excesses" of EGRET observations compared with the conventional model of diffuse γ-ray emission in $\gtrsim$GeV energy band (Hunter et al. 1997). However, since it is not the main purpose of the present work, we just briefly discuss the "GeV excess" problem for the sake of completeness and do not intend to go deep in this topic.

spectrum of the proton or electron should be harder than the one observed at the Earth; 2), the CRs of the source population need to reside in the Cygnus region in order not to exceed the locally measured CR fluxes. In this work we investigate this possible explanation in detail by building realistic models and deriving their implications for future experiments.

This paper is organized as follows: in Sec.2 we give an introduction to the diffuse γ-ray emission predicted by conventional GCR model. In Sec.3 we present a brief introduction to the "GeV excess" problem. Our models to solve the "TeV excess" problem and possible observational effects for future experiments are discussed in Sec.4. Finally the conclusion is drawn in Sec.5.

2. Diffuse γ-rays from the Conventional GCR model

The GCRs propagate diffusively in the Galactic magnetic field (see e.g., Gaisser 1990). The interactions between CRs and the interstellar medium (ISM) can generate diffuse γ-rays during propagation. A numerical solution of the diffusion equation is developed by Strong & Moskalenko (1998), which is known as the GALPROP model. In GALPROP the model parameters are adjusted to reproduce the locally measured CR spectra. The realistic distributions of ISM and ISRF are incorporated in GALPROP to calculate the fragmentations and energy losses. Since the realistic astrophysical inputs and the general treatments of relevant physical processes, such as convection and reacceleration, the GALPROP is recognized as the best CR propagation model at present.

We adopt the conventional GALPROP model to calculate the GCRs propagation and the γ-ray emission (hereafter we denoted this component as "GCR background"). The isotropic extra Galactic (EG) component of diffuse γ-rays is included (Sreekumar et al. 1998; Strong et al. 2004a). The results are shown in Fig.1. The EGRET data are adopted from the diffuse sky maps with the point sources from 3EG catalog subtracted (Cillis & Hartman 2005). The figure shows that the GALPROP prediction matches well with the low energy measurements of EGRET data (except the "GeV excess"), while for the TeV data of Milagro, it shows a remarkable under-estimation. The model prediction is about 6 times lower than observation. This is consistent with the results given in Abdo et al. (2008). It has been shown that even the optimized GALPROP model, which is developed to solve the EGRET "GeV excess" problem (see the next section), predicts only a half of the Milagro data (Abdo et al. 2007a, 2008). Therefore there must be an additional photon component with harder spectrum in the Cygnus region. We also note that the local high density of ISM or ISRF in the Cygnus region can not account for this "TeV excess" without violating the EGRET observations, since it just makes the curves shift upwards.

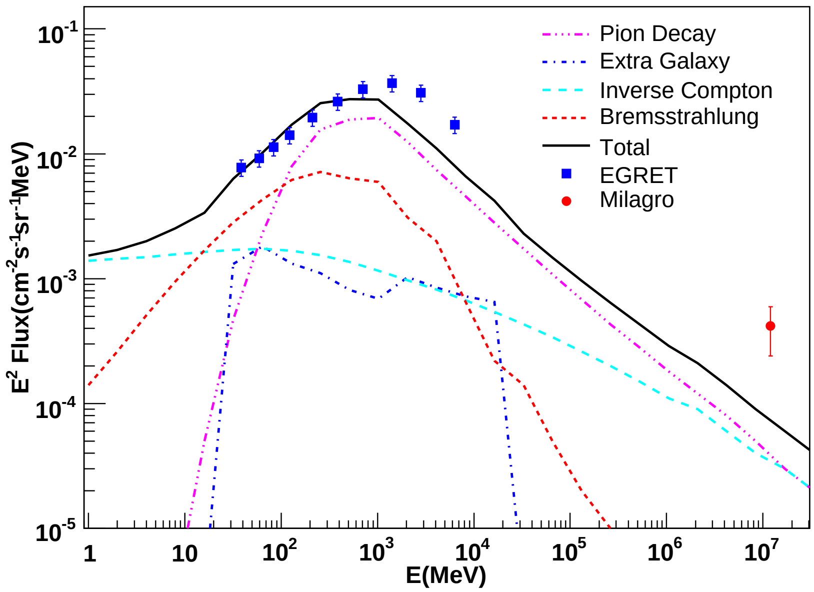

Fig. 1.— The diffuse γ-ray spectrum in the Cygnus region predicted by the conventional GALPROP model compared with the observational data from EGRET (Cillis & Hartman 2005) and Milagro (Abdo et al. 2007a).

3. The GeV excess

The Galactic diffuse γ-rays measured by EGRET show an excess for energies $\gtrsim$GeV compared with predictions by the conventional GCR model, which is referred as "GeV excess" problem (Hunter et al. 1997). The "GeV excess" appears in all directions of the sky, and there is no special structure in the Cygnus region. Many models are proposed to solve the "GeV excess" problem by tuning the CR spectra, such as the harder nucleon spectrum model (Gralewicz et al. 1997; Mori 1997), the harder electron spectrum model (Porter & Protheroe 1997; Pohl & Esposito 1998) or the combination of the two models (Strong et al. 2000). However, these models usually cannot reproduce the all-sky γ-ray data (Strong et al. 2004b).

Strong et al. (2004b) have developed an "optimized" model by adjusting the interstellar proton and electron intensities to reproduce the γ-ray data and CR data, such as B/C, simultaneously. The optimized model gives a good fitting to the EGRET data of all sky directions. However, large spatial fluctuations of proton and electron fluxes have to be incorporated in their model (Strong et al. 2004b).

Another approach to the "GeV excess" problem is by DM annihilation (de Boer 2005; de Boer et al. 2005; de Boer 2007). The EGRET data in all directions are in good agreement with predictions after taking the DM annihilation into account if assuming a supersymmetric DM with mass $m_\chi \sim 50 - 70$ GeV (de Boer et al. 2005). Bi et al. (2008a,b) extended the DM scenario using DM subhaloes to account for the "boost factor" and calculate both the CR background and DM signals in more realistic propagation models. In the present work we adopt the model of Bi et al. (2008a) to fit the GeV data. However, it should be noted that it is far away from the final answer to the "GeV excess" problem. To go details of this issue is beyond the scope of the present study.

4. TeV excess

In this section we turn to the "TeV excess" problem. We introduce a high energy population of CRs to explain the Milagro data. It is known that the Cygnus region is rich in potential CR accelerators, such as the Wolf-Rayet stars (van der Hucht 2001), OB associations (Bochkarev & Sitnik 1985) and supernova remnants (SNRs, Green 2004). Here we assume there exist a (or several) CR accelerating source(s) in this region. The ages of the sources should not be too old (e.g., $10^6 \sim 10^7$ yr, for typical diffuse coefficient $D \sim 10^{28}$ cm^2 s^{-1}, the propagation length after this time is about several hundred pc) so that the CRs can distribute diffusively in the Cygnus region and will not affect the measurements of CR fluxes at the Earth. We discuss in detail the hadronic and leptonic scenarios in the following.

4.1. The hadronic model

We first consider a proton source uniformly distributed in the Cygnus region. We assume it has the energy spectrum as $\mathrm{d}\phi_p/\mathrm{d}E_p \propto E_p^{-\alpha_p} \exp(-E_p/E_p^c)$. The spectrum index α_p is adopted as 2.3, which can well reproduce the Milagro data and is still consistent with the low energy data by EGRET. It should be noted that the adoption of α_p is not arbitrary. On one hand, it cannot be too soft in order not to exceed the sub-GeV observations by EGRET. On the other hand, the Fermi acceleration of CRs from shock waves predicts spectrum index ~ 2 (Gaisser 1990); and the diffusion in the interstellar medium can soften the spectrum a bit (e.g., 1/3 for a Kolmogorov diffusion). Therefore the Milagro observations can indeed limit the source spectrum in a relative narrow range. The cut-off energy E_p^c is due to the acceleration limit of the source. For supernova blast shock it is known to be $100 \sim 1000$ TeV for protons (Berezhko 1996). The shock acceleration by stellar winds of red giants and Wolf-Rayet stars gives 10 PeV (Voelk & Biermann 1988). The ensemble shocks of OB

association can even give the maximum energy about 100 PeV (Bykov & Toptygin 1990). Here we adopt the cut-off energy to be $1 \sim 10$ PeV. Such a cut-off seems not to affect the results of γ-rays at ~ 10 TeV. However, it will affect the high energy neutrino flux, as shown below. The normalization of the CR proton density is tuned to be consistent with the high energy observations by Milagro.

The γ-ray spectrum after taking such new sources into account is shown in Fig.2. It shows a good agreement between the model prediction and observations. We notice that the high energy behavior of γ-rays is dominated by the new proton source contribution, so precise measurements of the high energy spectrum (from several GeV to hundreds of TeV) will be helpful to determine the spectrum of the source term. The total energy of the proton source is estimated as $W(>1\ \mathrm{GeV}) \sim 10^{51}(\frac{1\ \mathrm{cm}^{-3}}{n_H})(\frac{d}{1\ \mathrm{kpc}})^2$ erg. For typical ISM density $n_H \approx 1\ \mathrm{cm}^{-3}$ and the distance of the source $d \sim 1$ kpc (which is comparable with the molecular clouds and OB associations in this region, Schneider et al. 2006), the total energy is similar with the energy release of a typical core-collapse supernova (Zwicky 1962).

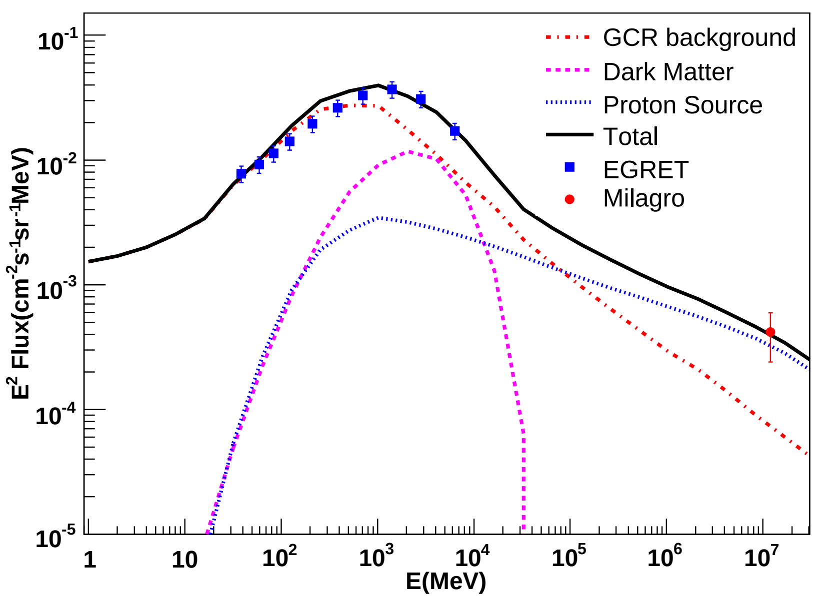

Fig. 2.— The energy spectrum of diffuse γ-rays in the Cygnus region as measured by EGRET and Milagro and predicted by the GALPROP model combined with additional proton source and DM annihilation components. See text for details.

For inelastic $p-p$ collision, the pion mesons π^+, π^- and π^0 are generated with almost equal amount (Gaisser 1990). γ-rays are produced through the decay of π^0 mesons. The

decay of $\pi^{\pm}$ will lead to neutrino emission. In general the initial neutrino flavor ratio is $\nu_e : \nu_\mu : \nu_\tau = 1 : 2 : 0$. Because of neutrino oscillation the flavor ratio on the Earth becomes $\nu_e : \nu_\mu : \nu_\tau = 1 : 1 : 1$. The ratio between the total number of neutrinos and γ-ray photons is $3 : 1$. The typical energy of neutrinos is $\sim 1/2$ of the γ photons, so we have (Beacom & Kistler 2007)

$$\frac{\mathrm{d}\phi_\nu}{\mathrm{d}E_\nu} = 2\frac{\mathrm{d}\phi_\gamma}{\mathrm{d}E_\gamma}, \tag{1}$$

for each kind of neutrinos.

In Fig. 3 we show the cumulative muon flux induced by $\nu_\mu + \bar{\nu}_\mu$ on a km^3 detector, like IceCube, for one-year observation. The muon flux including both the containing events (that muons generated in the detector) and the through-going events (that muons generated outside the detector and propagates into the detector volume) is calculated following the method of Kistler & Beacom (2006). The absorption of neutrinos by the Earth along the Cygnus direction (R.A. $\sim 20^h$, Dec. $\sim 40^\circ$) is taken into account. This absorption effect is known to be significant for neutrino energies greater than $\sim$ 10TeV (Lipari 2006). The background induced by the atmospheric neutrinos is also shown in the figure, which is from a 102 deg^2 sky region with two $3^\circ \times 3^\circ$ areas around the two TeV sources, TeV J2021+4130 and MGRO J2019+37, excluded (Abdo et al. 2007a). The atmospheric neutrino flux is adopted from Honda et al. (2007), with the zenith angle $\cos\theta_z \sim 0.6 - 0.7$ [3].

It can be seen from Fig. 3 that if the cut-off energy of protons is high enough, the neutrino induced muons are marginally observable over the atmospheric background for energy $>$ 10 TeV. For a 15-year observation of IceCube, we estimate the significance $\sim 3\sigma$ for an energy threshold 10 TeV. Compared with the neutrino emission from MGRO J2019+37 (Beacom & Kistler 2007), our result of diffuse neutrinos is ~ 4 times larger. This is reasonable as the total diffuse TeV photon emission is about 4 times larger than that from MGRO J2019+37 (Abdo et al. 2007a). However, since the diffuse atmospheric background is about 30 times higher than the case of MGRO J2019+37, the detectability becomes worse (Beacom & Kistler 2007). Kistler & Beacom (2006) got the similar conclusion about the diffuse neutrinos. If the cut-off energy of protons is as low as $\sim$ 1 PeV, the signal is dominated by the atmospheric background and is almost invisible.

It should be pointed out that the neutrinos from the GCRs cosmic rays interacting with the ISM are negligible and not shown here. From Fig.1 we can see that the π^0 component of γ-ray flux from GCR background is about one order of magnitude lower than the Milagro

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[3] The zenith angle of the Cygnus region relative to the detector at the South pole is about 130°, i.e., the neutrinos are up-going. Since there is a mirror symmetry between the up-going and down-going atmospheric neutrinos, it is equivalent to the atmospheric neutrino at direction with zenith angle $\sim 50^\circ$.

data. Therefore the neutrino emission from this component is also very small. It can also be noted that the diffuse γ-ray emission is actually not uniformly distributed in the Cygnus region, but concentrates in some areas. Therefore the atmospheric background will be lower if proper observational region is concentrated, and then the detectability of signals will be improved.

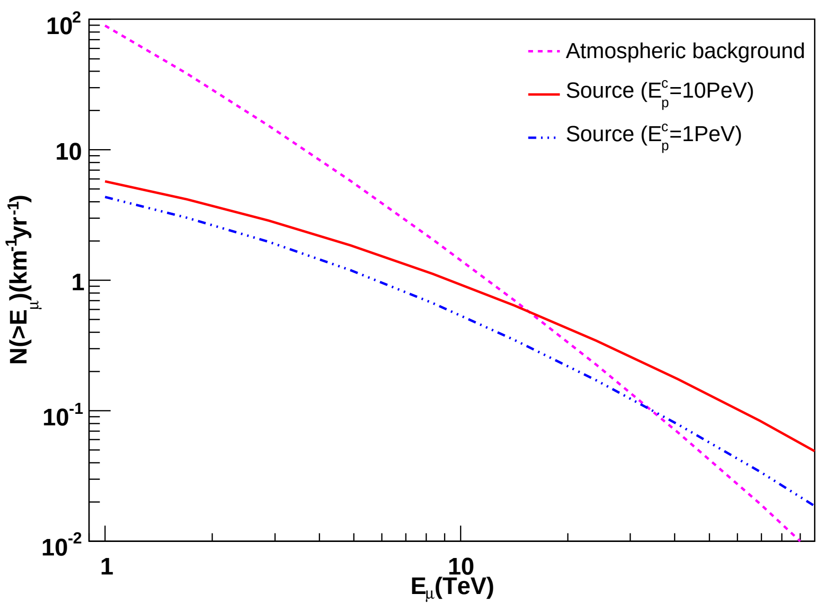

Fig. 3.— The cumulative muon events induced by neutrinos from the Cygnus region and atmospheric background on IceCube for one-year observation.

4.2. The leptonic model

A high energy electron population similar with the hadronic one is also able to produce the TeV γ-rays through IC scattering (Aharonian et al. 2006). Similar with the hadronic model, an electron source population with differential energy spectrum $\mathrm{d}\phi_e/\mathrm{d}E_e \propto E_e^{-\alpha_e}\exp(-E_e/E_e^c)$ is introduced to account for the TeV γ-ray emission. The high energy spectral index of the electron population is adopted as $\alpha_e = 2.6$, which is harder than the Galactic background electron spectrum ~ 3.3. The cut-off energy is adopted as $E_e^c \sim 100 - 1000$ TeV. Note that due to the fast energy losses of electrons in interstellar magnetic field, the maximum energy of electrons generally cannot be higher than several hundred TeV (Gaisser 1990).

However, such an electron population will contribute too many low energy γ-rays

through bremsstrahlung radiation and will exceed the EGRET data. Therefore a broken power-law of spectral index is introduced to match the data. We adopt $\alpha_e = 1.5$ for energy lower than 4 GeV, which is similar to that done in GALPROP (Strong et al. 2004a).

For the high energy slope, it is not arbitrary due to observations and theoretical arguments. It is known that the fast energy loss through synchrotron and IC will soften the power index of electron spectrum by about 1. Therefore if the source spectrum is ~ 2 as expected from 1st order Fermi acceleration, the propagated one is ~ 3. However, we argue that the reacceleration of electrons by the stellar wind shock of massive stars in the Cygnus region can maintain a harder spectrum — 2.6 as we adopted.

The target ISRF field is adopted as the combination of three components: CMB, infrared from dust and optical from stars (Porter 2005). The predicted γ-ray spectrum is shown in Fig.4. It shows that this model can also give good description to data. The total energy of this electron source is estimated as $W(> 1 \text{ GeV}) \sim 10^{49}(\frac{d}{1 \text{ kpc}})^2$ erg.

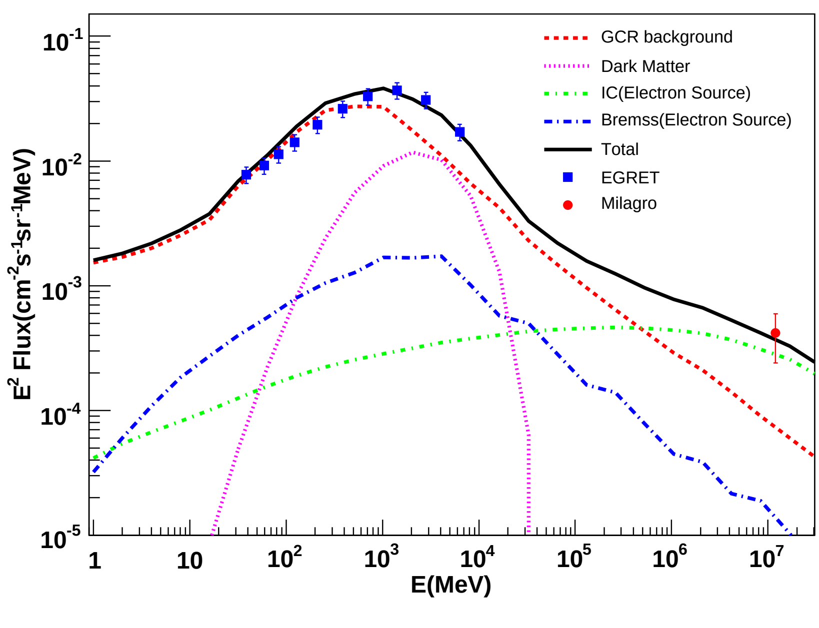

Fig. 4.— The energy spectrum of diffuse γ-rays in the Cygnus region as measured by EGRET and Milagro and predicted by the GALPROP model combined with additional electron source and DM annihilation components. See text for details.

It is expected that such a high energy electron population will generate low energy synchrotron radiation in the interstellar magnetic field. We show the synchrotron radiation in Fig.5 for the magnetic field $B = 1$, 3 and 10 μG respectively. The synchrotron spectrum

is $\sim (\alpha_e + 1)/2 = 1.8$, which is significantly different from the one by GCR background electrons, as shown in Fig.5.

Compared with the GCR background contribution, the additional electrons will contribute high energy synchrotron radiation, and might be detected by X-ray detectors. We find in the soft X-ray background (SXRB) from ROSAT All-Sky Survey (RASS, Snowden et al. 1997) that there is no distinct excess in the Cygnus region compared with nearby sky regions. The result from RASS in the Cygnus region is shown in this figure as an upper limit of the synchrotron radiation. It is shown that even for the magnetic field 10 μG the predicted synchrotron radiation in the soft X-ray band is consistent with the observational SXRB. However, the peak of the synchrotron radiation is in the hard X-ray band ($\sim$ hundred keV) if the electron source has an energy cut ~ 1 PeV. It may be detectable by the future satellite Hard X-ray Modulation Telescope (HXMT; Wu et al. 2002; Li et al. 2006). HXMT is a space satellite with high sensitivity and a field of view $5.7^\circ \times 5.7^\circ$, which is devoted to performing a hard X-ray all-sky imaging survey. The wide field of view and high sensitivity make it possible to detect the diffuse X-ray emission from the Cygnus region. The sensitivity curve of HXMT for the fix-direction observation of diffuse emission is shown in Fig.5. If the astrophysical background in hard X-ray band is not too high, the diffuse emission in the Cygnus region is detectable. If $E_e^c = 100$ TeV, the "TeV excess" of Milagro data can also be reproduced, but the synchrotron radiation is almost invisible due to the high SXRB.

5. Conclusions and Discussions

The TeV γ-ray emission of the Cygnus region observed by Milagro shows significant excess compared with the conventional CR model. In this work we introduce a high energy proton or electron source to explain this high energy γ-ray emission. It is shown that both the hadronic and leptonic models can give good explanation to the current data. The total energy needed for the source population is consistent with the typical energy output of a supernova.

The associated neutrino emission for the hadronic model and synchrotron radiation for the leptonic model are discussed as possible probes to discriminate these two scenarios. For the hadronic model, we estimate a 3σ significance for 15-year exposure of IceCube in case the protons cutoff energy reaches ~ 10 PeV. The non-null result of the neutrino detection will support the hadronic model. For the leptonic scenario, the synchrotron radiation by the electrons is more luminous at the X-ray wavelength. We show that if the energy cut-off of the electron source is as high as ~ 1 PeV, the synchrotron radiation will peak in the hard X-ray bands and it might be observable on the satellite HXMT.

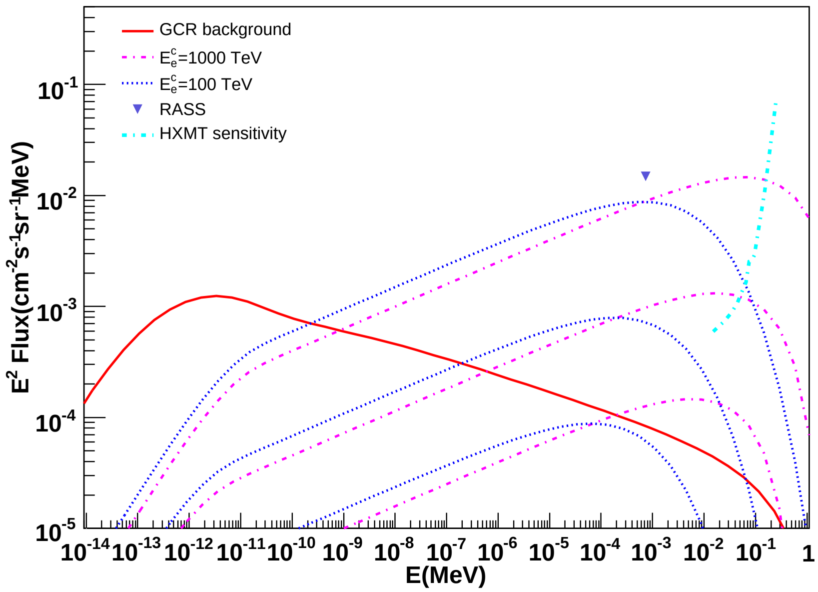

Fig. 5.— The synchrotron radiation from the electron source population for magnetic fields $B = 1$, 3 and 10μG (from bottom to top) respectively. The GCR background synchrotron radiation is calculated using GALPROP. The observed X-ray limit is from RASS (Snowden et al. 1997). Also shown is the sensitivity curve for fix-direction observation of HXMT.

In the calculation, the ISM density, the ISRF intensity and the magnetic field are adopted as typical Galactic values. Since there are a large number of massive stars and molecular clouds in the Cygnus region, the ISRF and ISM density may be higher than the Galactic average values. We should point out that this does not change the basic conclusion in this work. This is because a higher ISM density or ISRF intensity can be effectively compensated by a lower CR flux. For the hadronic model, the neutrino flux will keep the same since neutrino flux is proportional to the γ-ray flux. For the leptonic model a higher ISRF intensity will correspond to a lower electron luminosity. However, considering the magnetic field in the Cygnus region may be also stronger than the Galactic value we may expect similar synchrotron radiation as given in the work.

Finally, since the present data are lack in the energy interval from $\sim$ 10GeV to $\sim$ 1TeV due to the transition of detection technology from space to ground there are large uncertainties for model construction. The space telescope Fermi will extend the detection energy up to $\sim$ 300GeV (Ritz & GLAST Mission Team 2004). Together with some ground-

based experiments, such as ARGO, which may lower the energy threshold down to $\sim$ 100GeV (Bacci et al. 1999), we will have better understanding in the emission mechanism of this region in the future.

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